Connecting low-lying dipole modes to nuclear structure and equation of state

7^{th} International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX7)

Dipartimento di Fisica e Astronomia

Catania, June 11th - 16th, 2023

Authors: S. Burrello, M. Colonna

INFN - Laboratori Nazionali del Sud

Outline of the presentation

1. **Theoretical approaches for nuclear many-body problem**
   - Ab-initio vs phenomenological models based on energy density functionals (EDF)
   - Effective interaction and nuclear matter (NM) Equation of State (EoS)

2. **EDF-based models: recent results and further developments**
   - ✏ Mean-field dynamical models with phenomenological EDFs
     - Nature of low-lying dipole modes and connection with nuclear structure
     - Correlation between low-lying dipole excitations and properties of EoS
   - ✏ Extensions of EDF approaches: bridge with ab-initio and beyond mean-field
     - Benchmark ab-initio for low-density pure neutron matter (PNM)
     - Embedding many-body correlations and clustering phenomena

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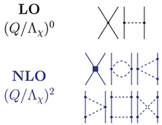
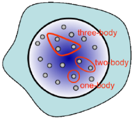
- **Ab-initio** approaches based on **many-body** expansion
  - Realistic or **effective field theory** (EFT) interactions
    $\Rightarrow$ Diagrammatic hierarchy (**power counting**)





- **Phenomenological** models with **effective** interaction
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  - Fit of parameters to reproduce various data

- Energy Density Functional (**EDF**) theory
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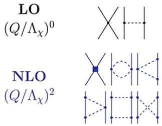

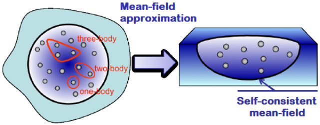

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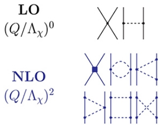

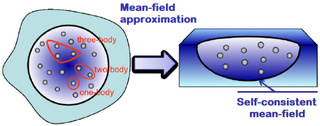

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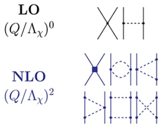

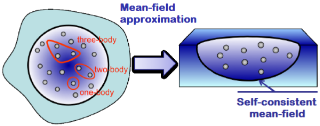

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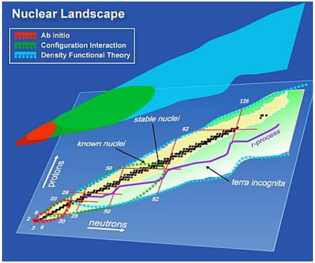

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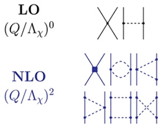

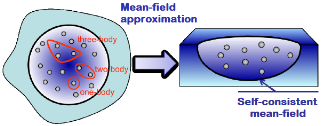

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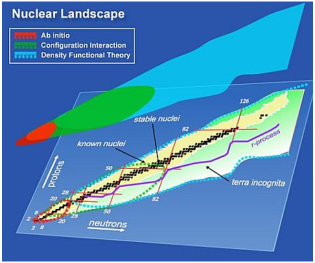

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Recent attempts to bridge EFT with EDF theories

Physics Letters B 811 (2020) 135938

Contents lists available at ScienceDirect

Physics Letters B

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Towards a power counting in nuclear energy–density–functional theories through a perturbative analysis

Stefano Burrello [a,*], Marcella Grasso [a], Chieh-Jen Yang [b]

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PHYSICAL REVIEW C **106**, L011305 (2022)

Letter

Calculations for nuclear matter and finite nuclei within and beyond energy-density-functional theories through interactions guided by effective field theory

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[2] Nuclear Physics Institute of the Czech Academy of Sciences, 25069 Řež, Czech Republic
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(Received 4 October 2021; accepted 24 June 2022; published 21 July 2022)

Collective excitations: neutron skin and EoS

- **Collective phenomena** in **many-body** dynamics $\Rightarrow$ properties of **interaction**
- **Dipole excitations** in nuclei:
  - Giant Dipole Resonance (GDR)
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- **Isovector** terms of **effective interaction**

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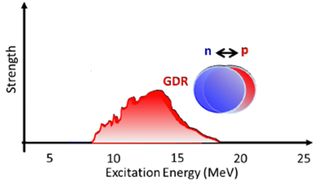

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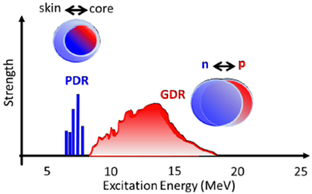

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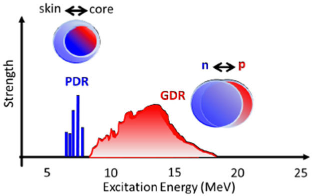

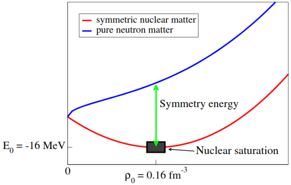

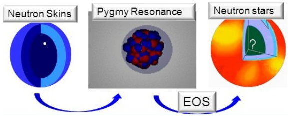

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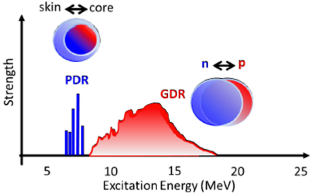

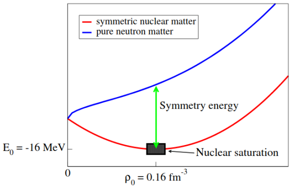

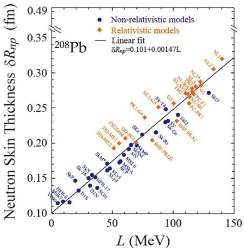

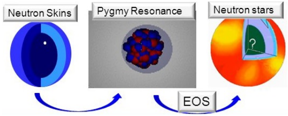

$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \dots$$

[X. Roca-Maza et al., PRL 106 (2011)]

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Mean-field dynamics and dipole excitations

- **Mean-field** dynamical models with **non-relativistic** Skyrme-like EDFs

PHYSICAL REVIEW C **99**, 054314 (2019)

Interplay between low-lying isoscalar and isovector dipole modes: A comparative analysis between semiclassical and quantum approaches

S. Burrello,[1] M. Colonna,[1] G. Colò,[2,3] D. Lacroix,[4] X. Roca-Maza,[2,3] G. Scamps,[5,6] and H. Zheng[1,7]

- **Quantal** Time-Dependent-Hartree-Fock (**TDHF**) (or RPA for zero-amplitude)
  - **Comparison** also with semi-classical **Vlasov** calculations

    [S. Burrello, M. Colonna, and H. Zheng, Front. Phys. 7, 53 (2019)]

    [H. Zheng, S. Burrello, M. Colonna, and V. Baran, PRC 94, 014313 (2016)]

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- **Strength** function: $S_K(E) = \sum_n |\langle n| \hat{D}_K |0\rangle|^2 \, \delta(E - (E_n - E_0))$ $\qquad K = S, V$
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Nature and structure of low-lying dipole modes

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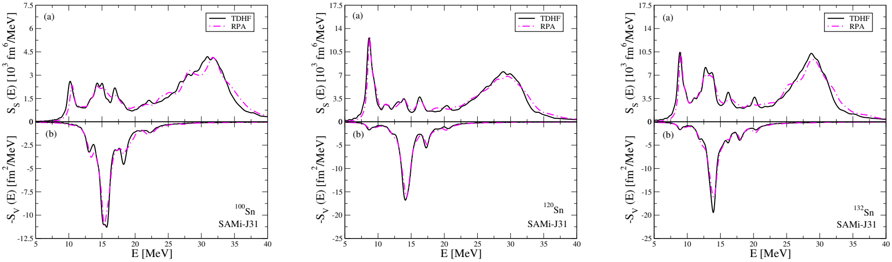

- PDR ⇒ **isoscalar-like** mode
  - IV component for **neutron-rich** nuclei
  - n and p move in **phase** for ^{100}Sn
  - involves the outer surface (**skin**)
- ^{120}Sn surface is more diffuse than ^{132}Sn (**open** vs **closed-shell** nucleus)

[S. Burrello et al., Phys. Rev. C 99, 054314 (2019)]

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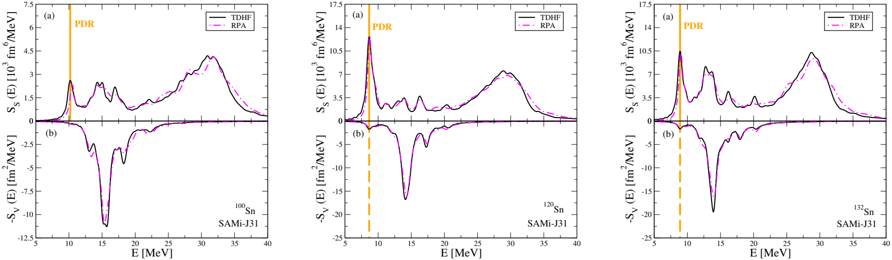

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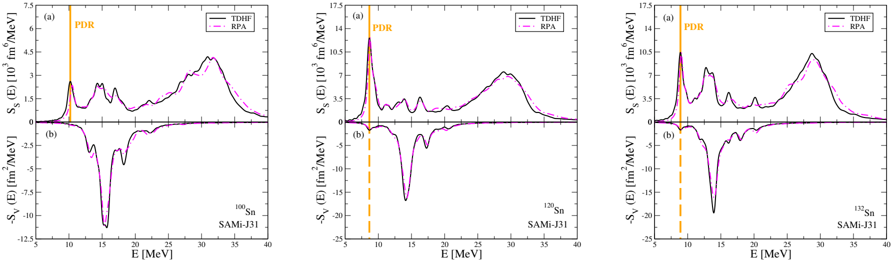

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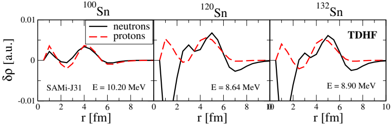

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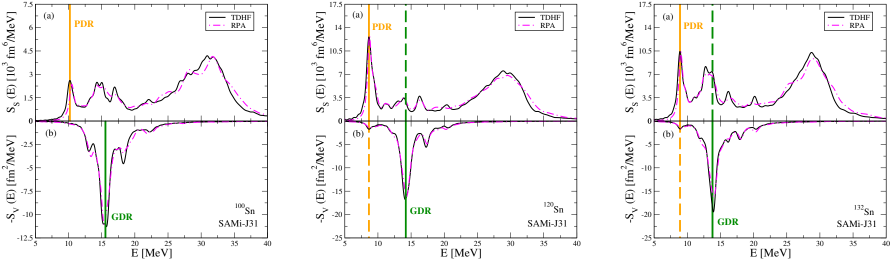

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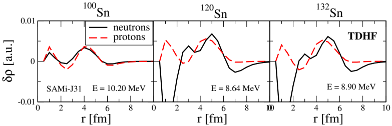

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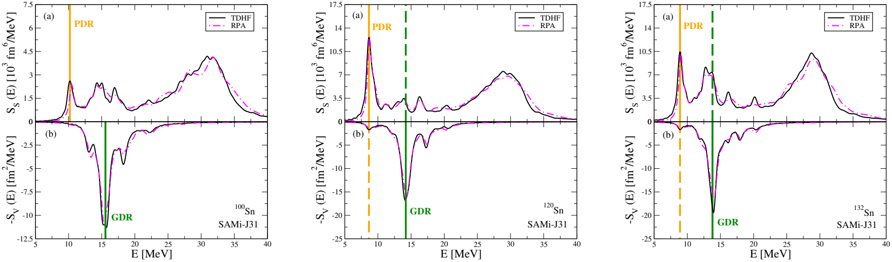

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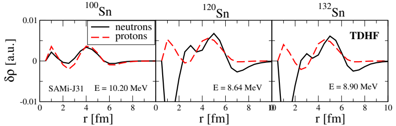
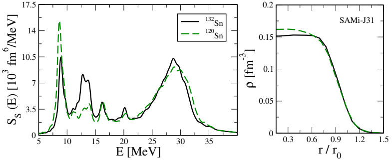
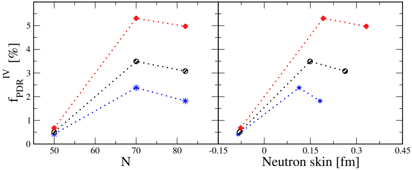




Evolution of IS/IV PDR along Sn isotopic chain

- **Question**: **IV** PDR fraction of **Energy Weighted Sum Rule** does not grow from N
- **Explanation**: it reflects the **decrease** in the **IS fraction** and IS dipole strength

[S. Burrello et al., Phys. Rev. C 99, 054314 (2019)]



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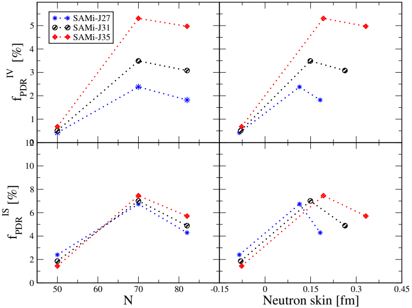

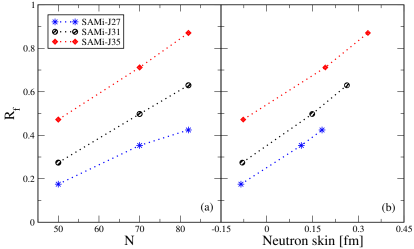

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Outline of the presentation

1. Theoretical approaches for nuclear many-body problem
   - Ab-initio vs phenomenological models based on energy density functionals (EDF)
   - Effective interaction and nuclear matter (NM) Equation of State (EoS)

2. **EDF-based models: recent results and further developments**

   ✏ Mean-field dynamical models with phenomenological EDFs
   - Nature of low-lying dipole modes and connection with nuclear structure
   - Correlation between low-lying dipole excitations and properties of EoS

   ✏ **Extensions of EDF approaches: bridge with ab-initio and beyond mean-field**
   - Benchmark ab-initio for low-density pure neutron matter (PNM)
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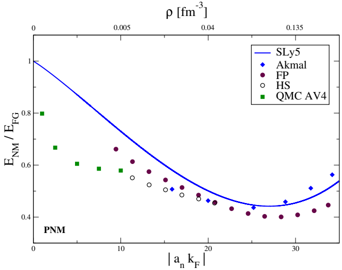
3. Summary and perspectives

EFT-inspired EDFs: YGLO and ELYO

- **Dilute** PNM (a_s = -18.9 fm) $\Rightarrow$ close to **unitary** limit of interacting **Fermi** gas
- **Lee-Yang** (LY) expansion in $(a_s k_F)$ from **EFT** ($\nu_i = 2, 4$ for PNM, SNM)

$$\frac{E}{N} = \frac{\hbar^2 k_F^2}{2m}\left[\frac{3}{5} + (\nu_i - 1)\frac{2}{3\pi}(k_F a_s) + (\nu_i - 1)\frac{4}{35\pi^2}(11 - 2\ln 2)(k_F a_s)^2 + \ldots\right]$$



- Combining **EDF** with LY expansion:
  - Yang Grasso Lacroix Orsay (YGLO)

[C.J. Yang, M. Grasso, D. Lacroix, PRC 94, 031301 (2016)]

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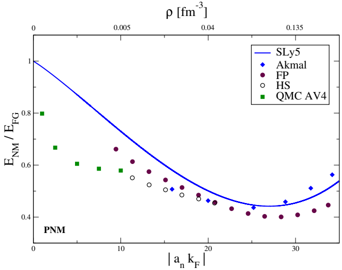

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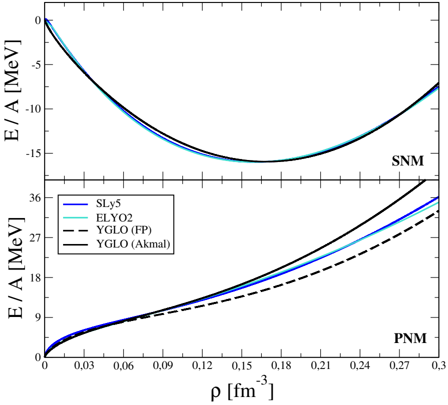

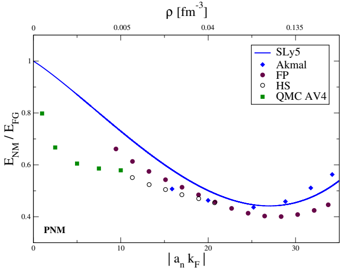

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- Potential part of YGLO functional ($a_i = -18.9(-20.0)$ fm, i = S, N)

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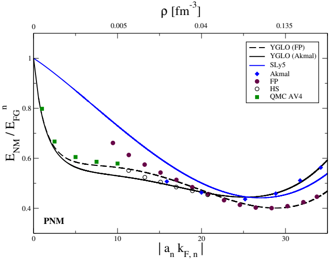

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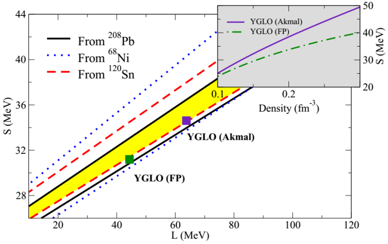

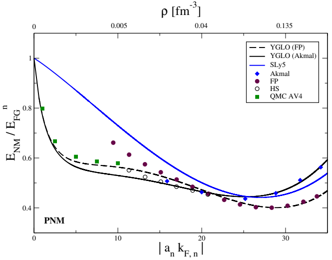

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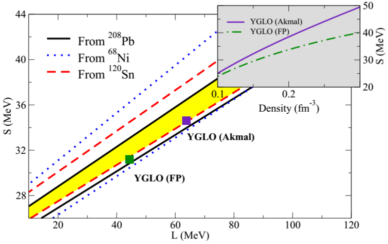

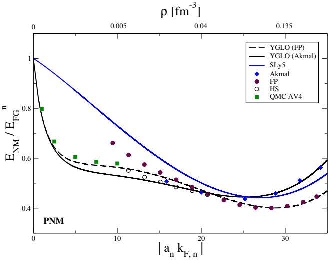

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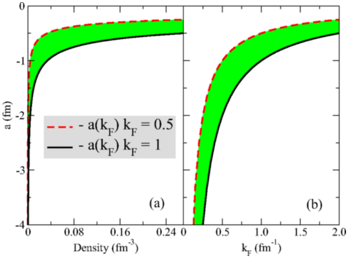
- Including LY p-wave contributions
- Mapping with s-wave Skyrme-like EDF



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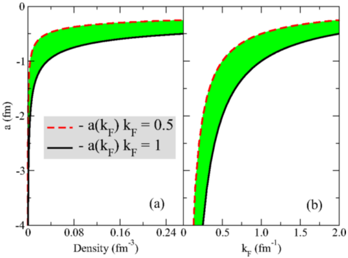

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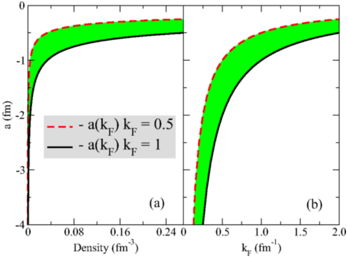
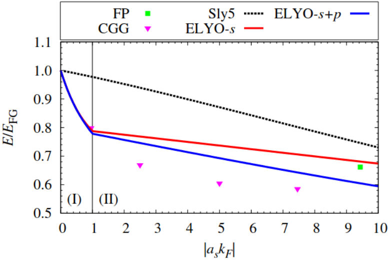
[J. Bonnard, M. Grasso, D. Lacroix, PRC 101, 064319 (2020)]





Energy of neutron drops and effective mass

- **Application** of YGLO and ELYO on finite systems ⇒ **neutron drops**

  [J. Bonnard, M. Grasso, D. Lacroix, PRC 98, 034319 (2018); PRC 103, 039901(E) (2021)]

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- Adjustment on **energy** values of drops available from ab-initio calculations
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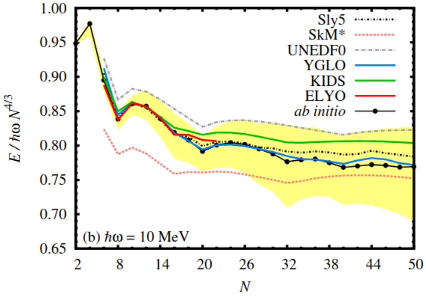

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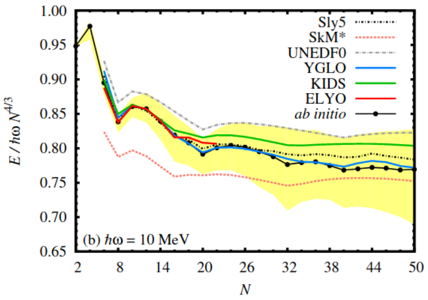
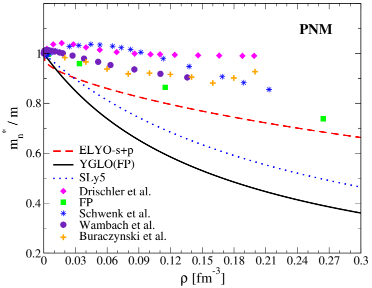




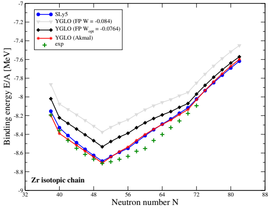
Finite nuclei and neutron drip-line with YGLO

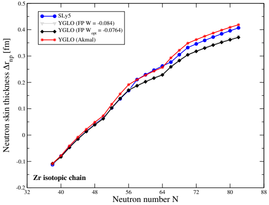
- **Hartree-Fock** calculations with YGLO: **ground state** properties

PHYSICAL REVIEW C **103**, 064317 (2021)

Application of an *ab-initio*-inspired energy density functional to nuclei: Impact of the effective mass and the slope of the symmetry energy on bulk and surface properties

Stefano Burrello[1,*] Jérémy Bonnard[2,†] and Marcella Grasso[1,‡]





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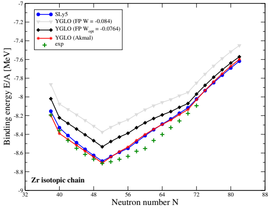

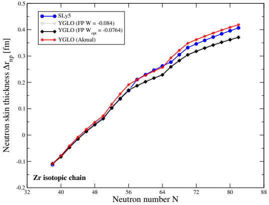

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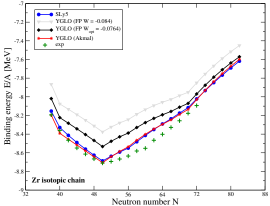

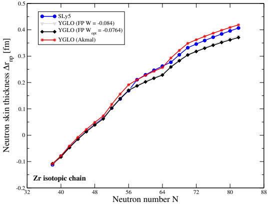

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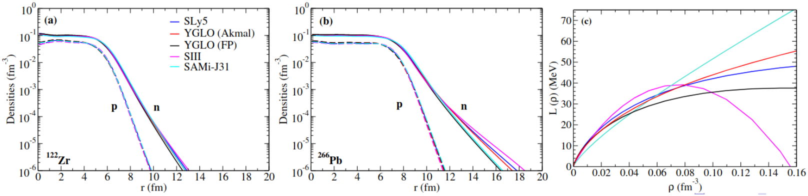

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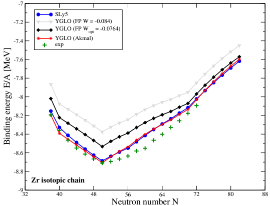
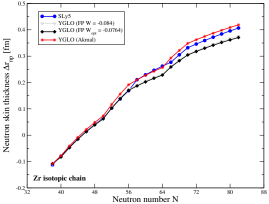
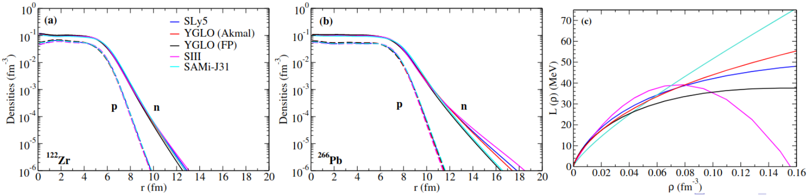




What next?

- Improving **effective mass** predictions
- **Implementation** in **dynamical** models

- **Correlation** between tail of **density profiles** and **slope** of $S(\rho)$ at low-density



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Embedding correlations and clusters in EDFs

- Many-body **correlations** at densities **below** ρ_0
  - Formation of nucleon **bound** states (clustering)
- **Phenomenological** EDF-based models with **clusters**
  - Generalized relativistic density functional (GRDF)

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- Modified Δr_{np} - L correlation [see talk of Z. Yang]

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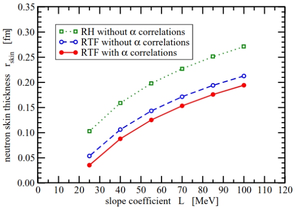

Embedding correlations and clusters in EDFs

- Many-body **correlations** at densities **below** ρ_0
  - Formation of nucleon **bound** states (**clustering**)
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- Modified Δr_{np} - L correlation [see talk of Z. Yang]

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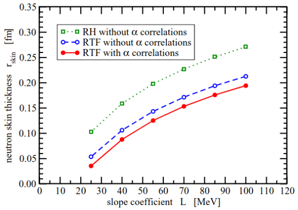
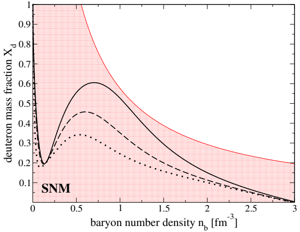
Eur. Phys. J. A (2022) 58:120 — The European Physical Journal A

Embedding short-range correlations in relativistic density functionals through quasi-deuterons

S. Burrello[1,a], S. Typel[1,2,b]





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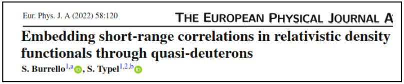
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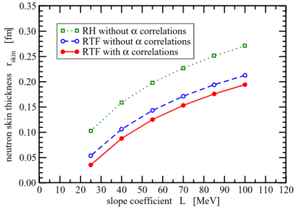

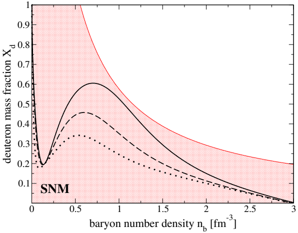

What next?

- Inclusion of **light clusters** (and quasi-deuterons) within a **kinetic** approach
- Study of collective **excitation modes** [in coll. with R. Wang + INFN CT]

Outline of the presentation

1. Theoretical approaches for nuclear many-body problem
   - Ab-initio vs phenomenological models based on energy density functionals (EDF)
   - Effective interaction and nuclear matter (NM) Equation of State (EoS)
2. EDF-based models: recent results and further developments
   - Mean-field dynamical models with phenomenological EDFs
   - Extensions of EDF approaches: bridge with ab-initio and beyond mean-field
3. Summary and perspectives

Final remarks and conclusions

Main topic

- **MF** calculations for nuclear **structure** and small amplitude **dynamics**
- Extension of EDFs to **bridge** with **ab-initio** approaches and include **clusters**

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- **Evolution** of low-lying modes with **density profiles** and **neutron skin**
- Application to **finite systems** of EDFs grounded on **ab-initio** at **low-density**
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Further developments and outlooks

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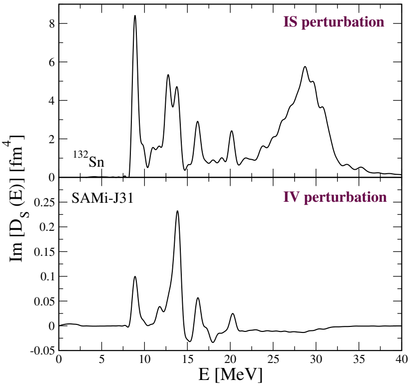
THANK YOU FOR YOUR KIND ATTENTION!

Back-up slides

Coupling between IS and IV modes

- **Symmetric** nuclear matter: **IS** and **IV** modes are **decoupled**
- **Neutron-rich** systems: n and p oscillate with **different amplitudes** ⇒ **coupling**



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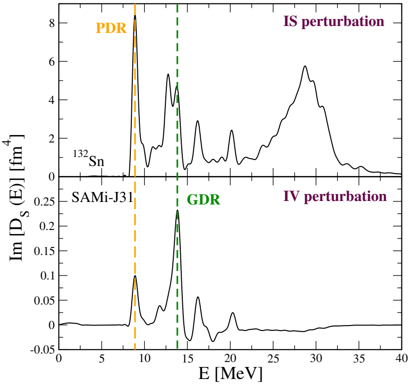

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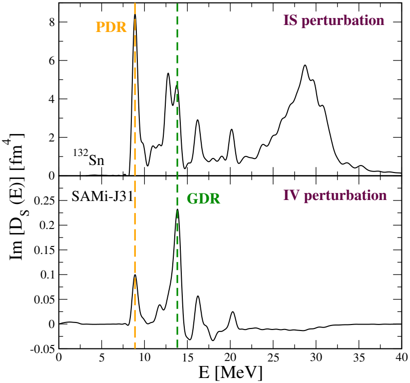

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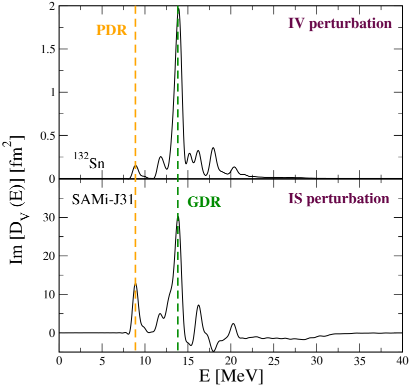
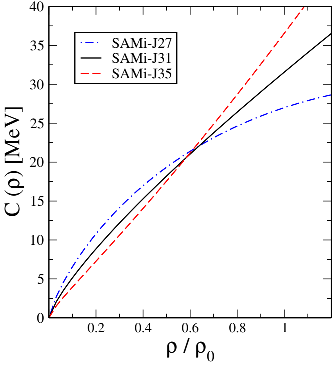


IV response

Influence of the effective interaction

- **SAMi-J** interactions
  [X. Roca-Maza et al., PRC87, (2013)]
  ⇒ isolate influence of **IV channel**
  $E_{sym}(\rho) = C(\rho) I^2$



- **Sensitivity** of $E_{IV\text{-}GDR}$ to E_{sym} at **crossing**
- Role of symmetry energy **slope**:
  - IV **PDR**
- **Agreement** with **Vlasov** results

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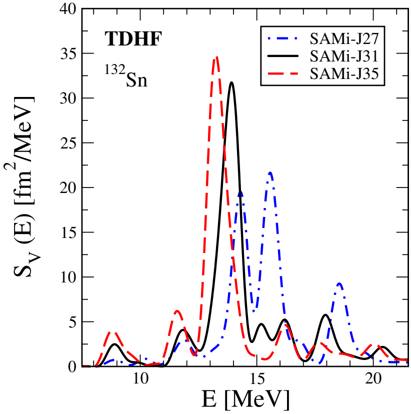

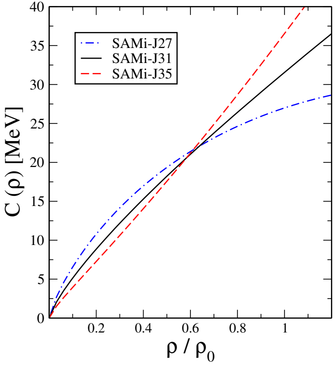

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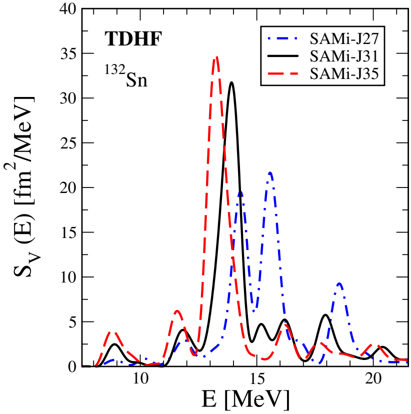

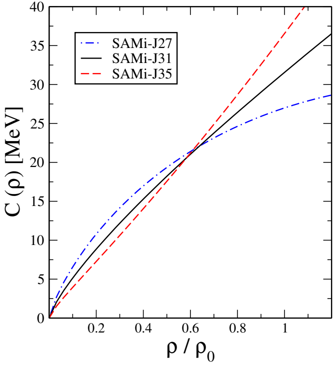

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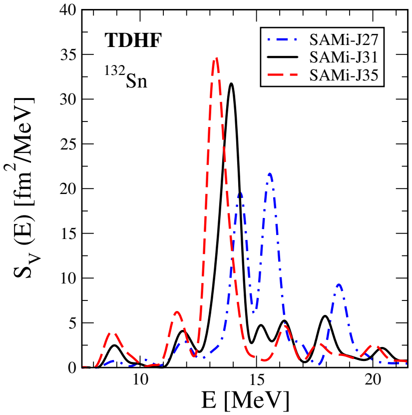

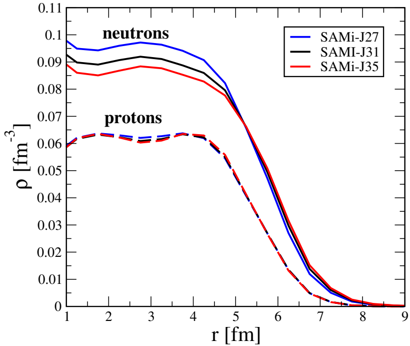

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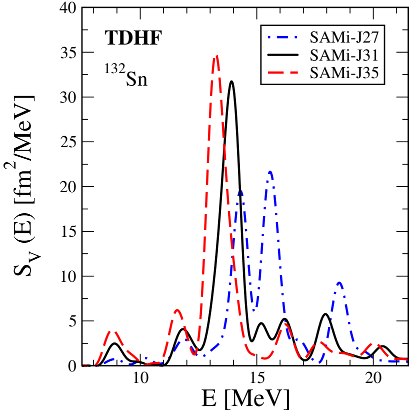
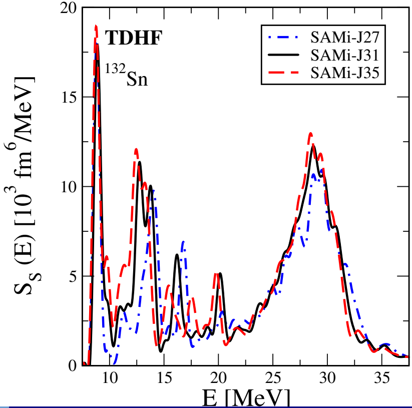
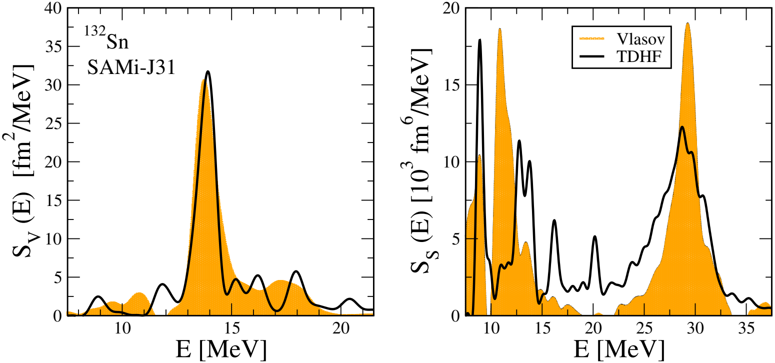




Comparison between Vlasov and TDHF model



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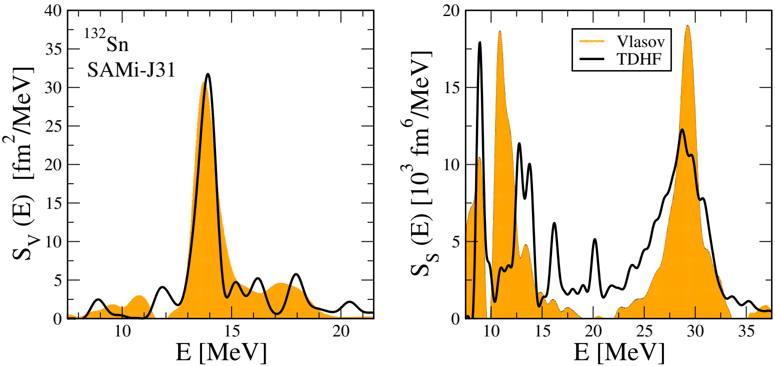

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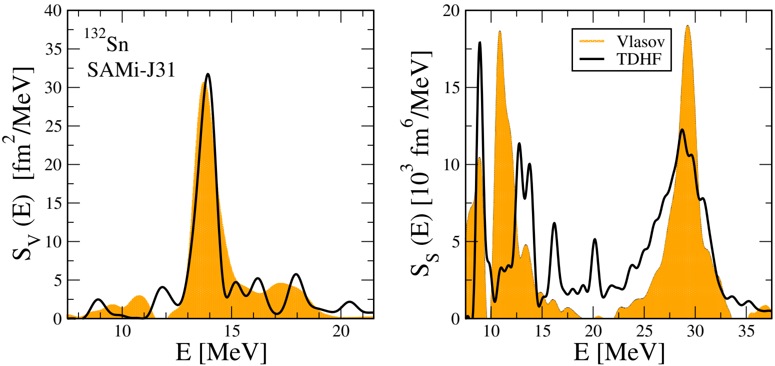

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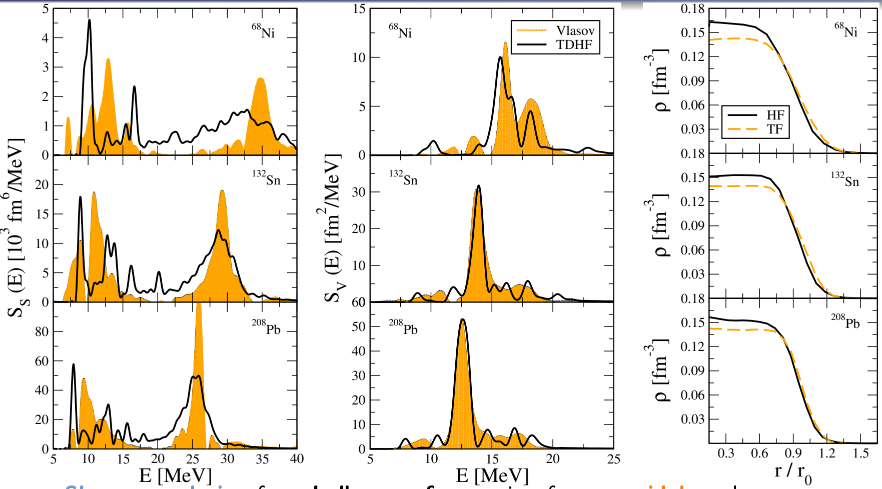
Link between nuclear response and density profiles



- **Sharper evolution** from **bulk** to **surface** region favor **toroidal** mode

  Smoother density profile leads to **robust PDR** oscillations

[S. Burrello et al., Phys. Rev. C 99, 054314 (2019)]

Comparison between TDHF and RPA

- **TDHF** and **RPA** **equivalent** in zero-amplitude limit, despite **technical procedures**
- Question: which **numerical parameters** ensure the best **agreement**?
- Dependence on **box size** (i.e. **discretization** of **continuum** single-particle states)

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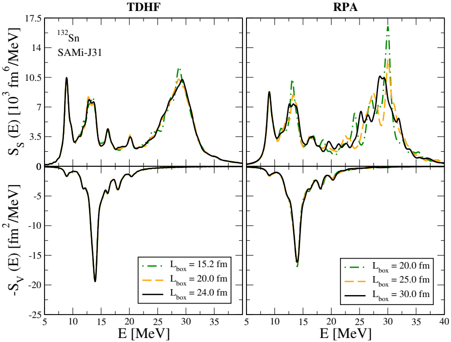

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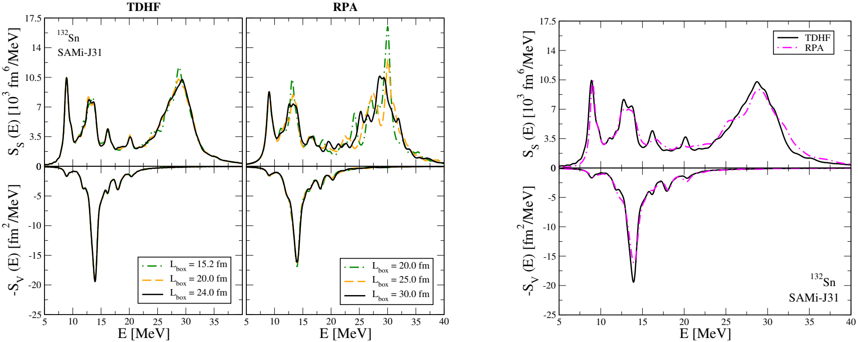

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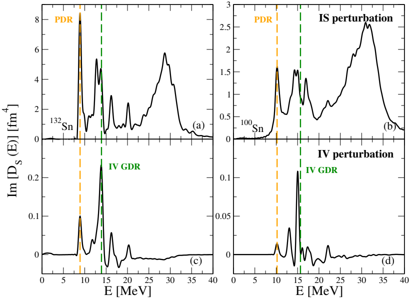
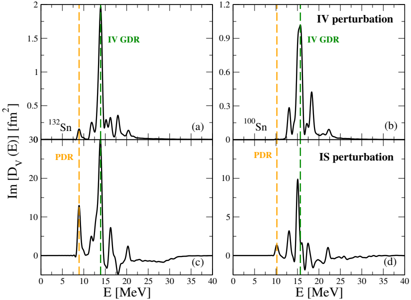
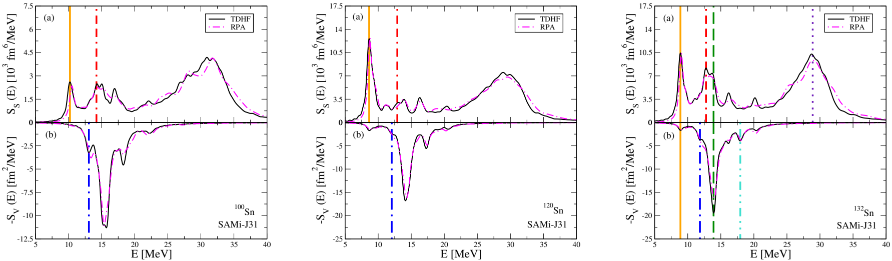
Back-up slides: focus on IS/IV mixing

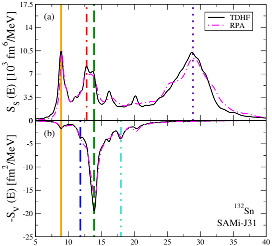


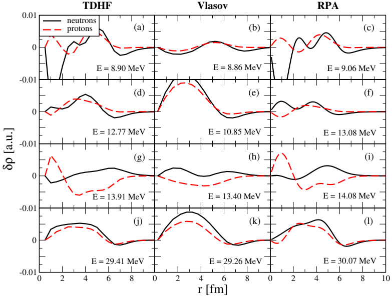


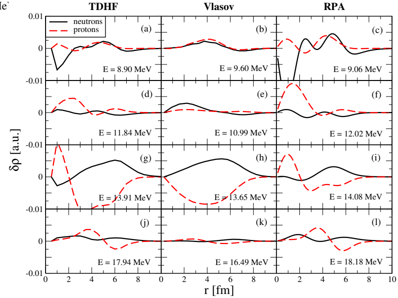
Back-up slides: dipole strength in Sn isotopes



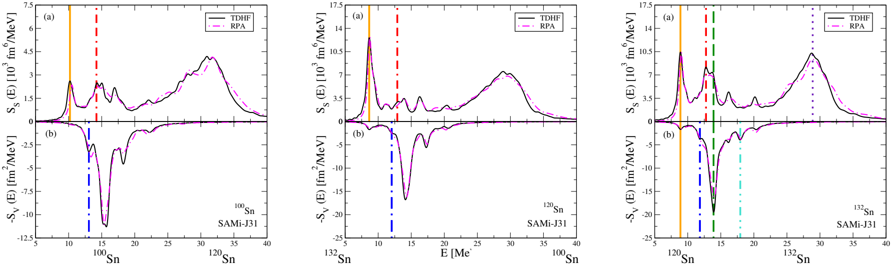
Back-up slides: transition densities comparison

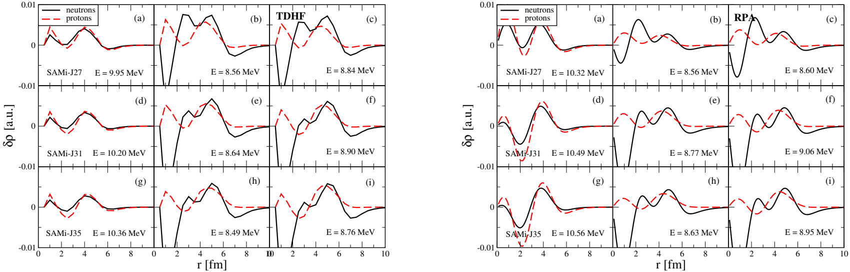






Back-up slides: transition densities of PDR





Back-up slides: torodail mode and 2nd IV peak